

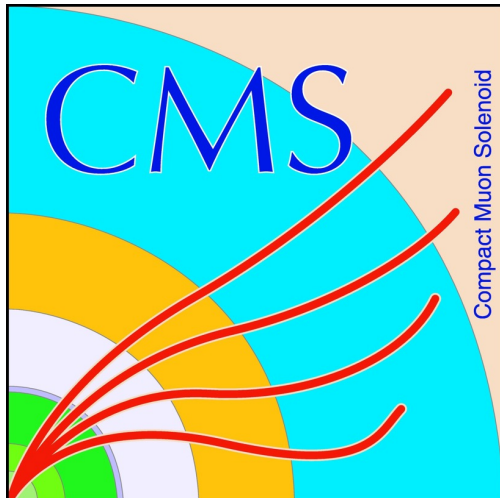


# Future Physics with CMS detector at HL-LHC

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On behalf of CMS experiment

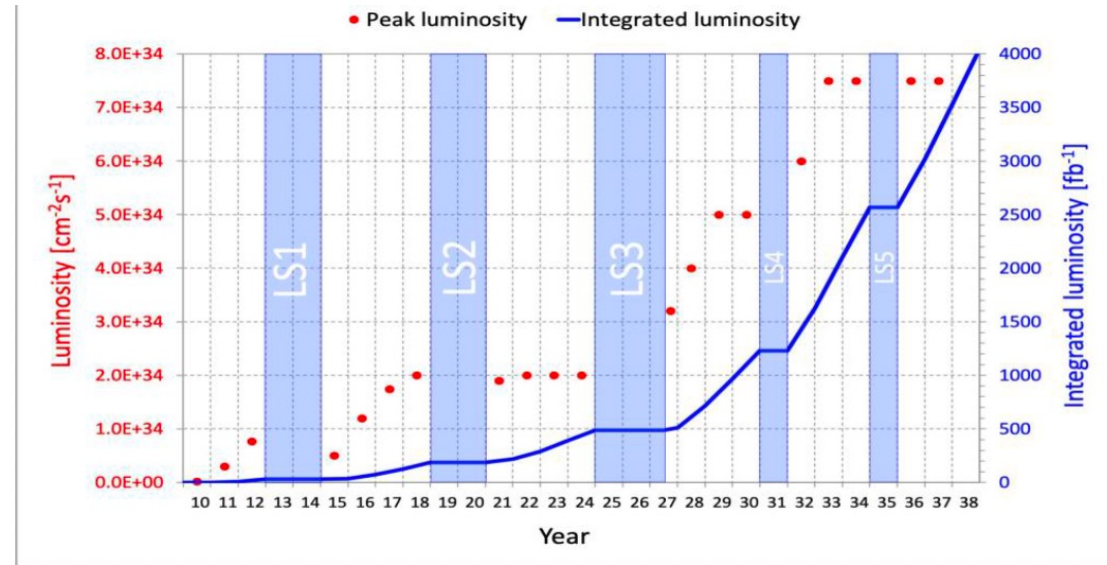


9<sup>th</sup> April 2024

WG6: Future Experiments,  
XXXI International Workshop on  
Deep Inelastic Scattering  
and Related Subjects (DIS2024),  
Grenoble, France

# The High Luminosity LHC (HL-LHC) Upgrade

HL-LHC goal is to achieve  $\approx 20x$  more data than recorded so far



Last updated: January 2022

- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning/magnet training



# Snowmass White Paper Contribution: ATLAS & CMS

## Physics with the Phase-2 ATLAS and CMS Detectors. [ATL-PHYS-PUB-2022-018](#)

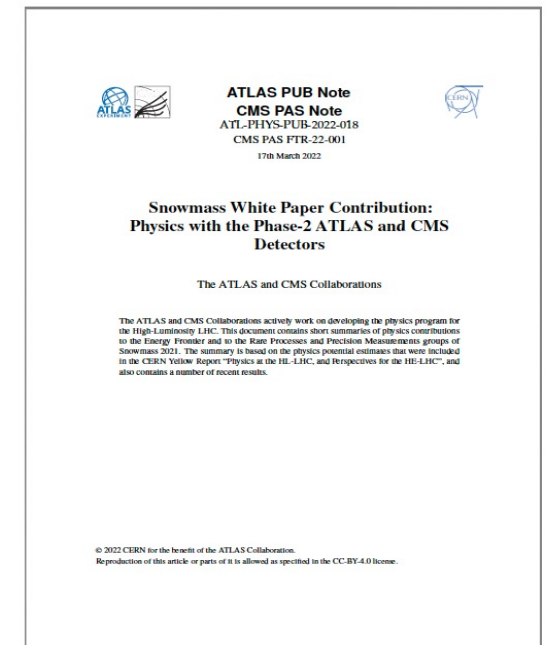
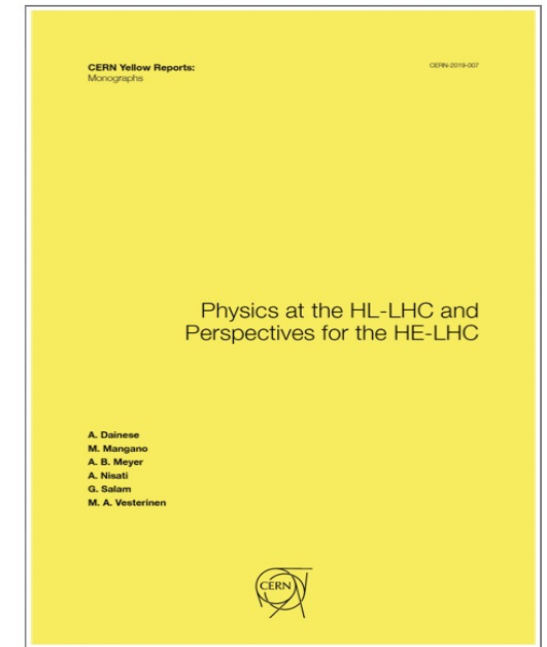
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Summary of earlier results  
- mainly from the 2018-19  
Yellow Reports (YRs)  
- 1-page summaries of new results

# Projections to HL-LHC

- **HL-LHC projection results mainly based on:**
  - 2018 Yellow Report
  - substantial update in the Snowmass2021 report
- **Strategies for the projection:**
  - extrapolations of (partial/full) Run-2 results to HL-LHC luminosity
  - parametric simulations based on upgraded detectors
- **Uncertainty schemes:**
- YR18 systematics uncertainties (baseline):
  - theoretical uncertainties: reduced by half
  - most experimental uncertainties: scaled down with  $1/\sqrt{L}$
  - luminosity uncertainty: aiming at 1%
  - uncertainties due to the limited number of simulated events are typically neglected
- alternatively, to understand the impacts of systematics
  - Run-2 systematic uncertainties
  - statistical-only uncertainties



# 4 tops

From the YR (2018):

“The production of four top quarks is one of the rare processes in top quark physics that has large sensitivity to variety of new physics effects (including effective field theory sensitivity and sensitivity to anomalous top-Higgs couplings), while at the same time it is interesting in the Standard Model context as a complex QCD process.

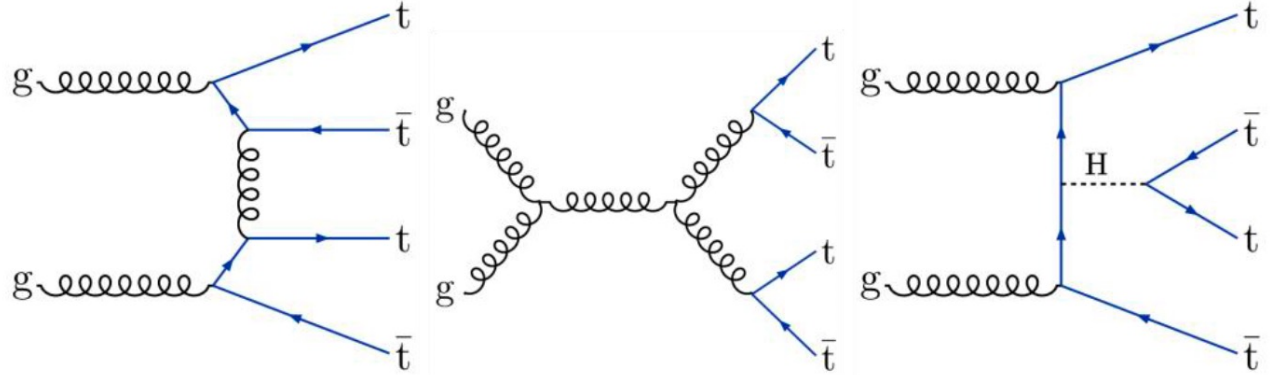
The production of  $t\bar{t}t\bar{t}$  is a rare SM process that is expected to be discovered by future LHC runs, including HL-LHC...

5 years later: CMS (ATLAS) announces evidence (observation) of the process!!!

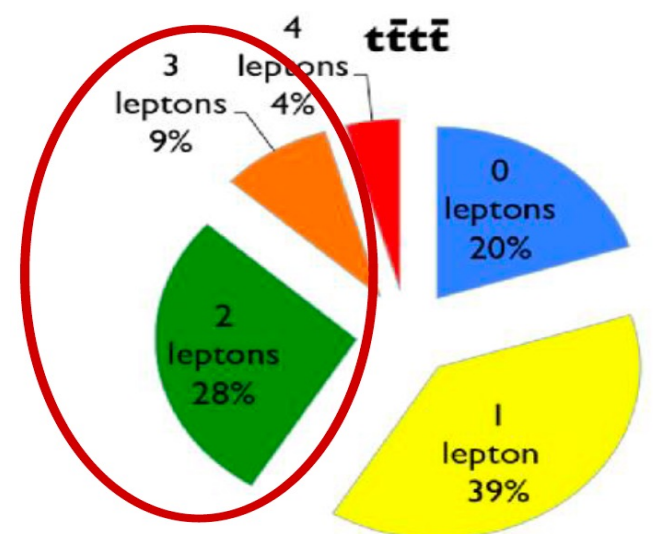
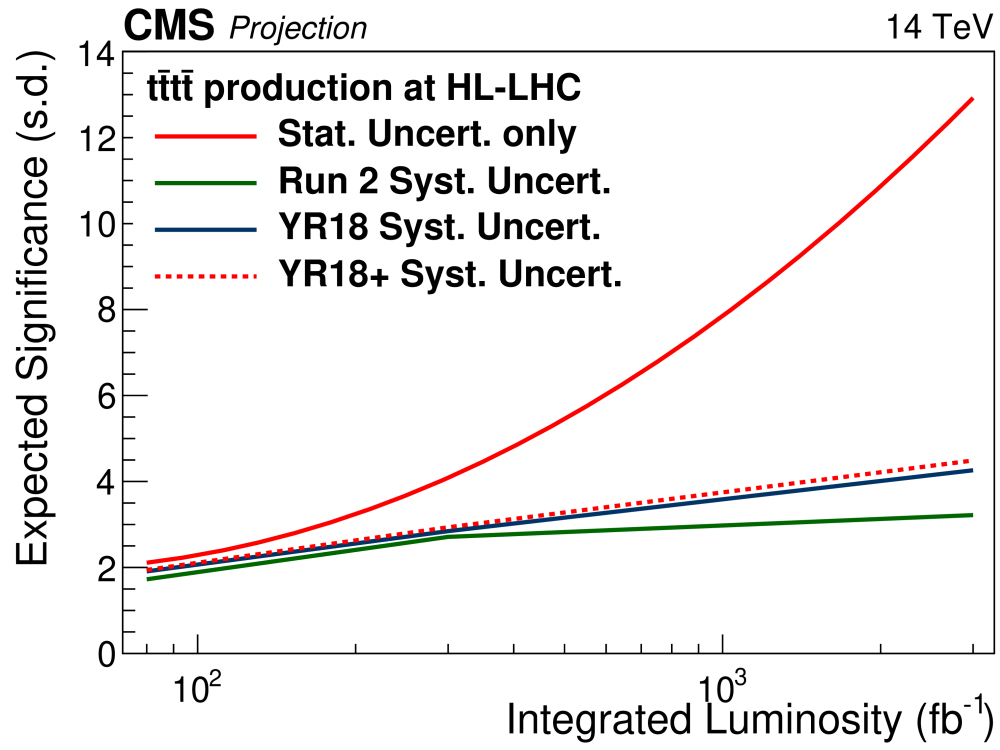
fully differential measurement at HL-LHC?

# 4 tops production

- Rare process sensitive to BSM Physics
- **Current sensitivity  $1\sigma$  with events with two or three leptons (during YR studies)**
- Expected uncertainty @HL-LHC 20-30%
- **Expect evidence of  $t\bar{t}t\bar{t}$  with  $3\text{ab}^{-1}$  at HL-LHC**



Int. Luminosity	$\sqrt{s}$	Stat. only (%)	Run-2 (%)	YR18 (%)	YR18+ (%)
$300\text{ fb}^{-1}$	14 TeV	+30, -28	+43, -39	+36, -34	+36, -33
$3\text{ ab}^{-1}$	14 TeV	$\pm 9$	+28, -24	+20, -19	$\pm 18$
$3\text{ ab}^{-1}$	27 TeV	$\pm 2$	+15, -12	+9, -8	+8, -7
$15\text{ ab}^{-1}$	27 TeV	$\pm 1$			

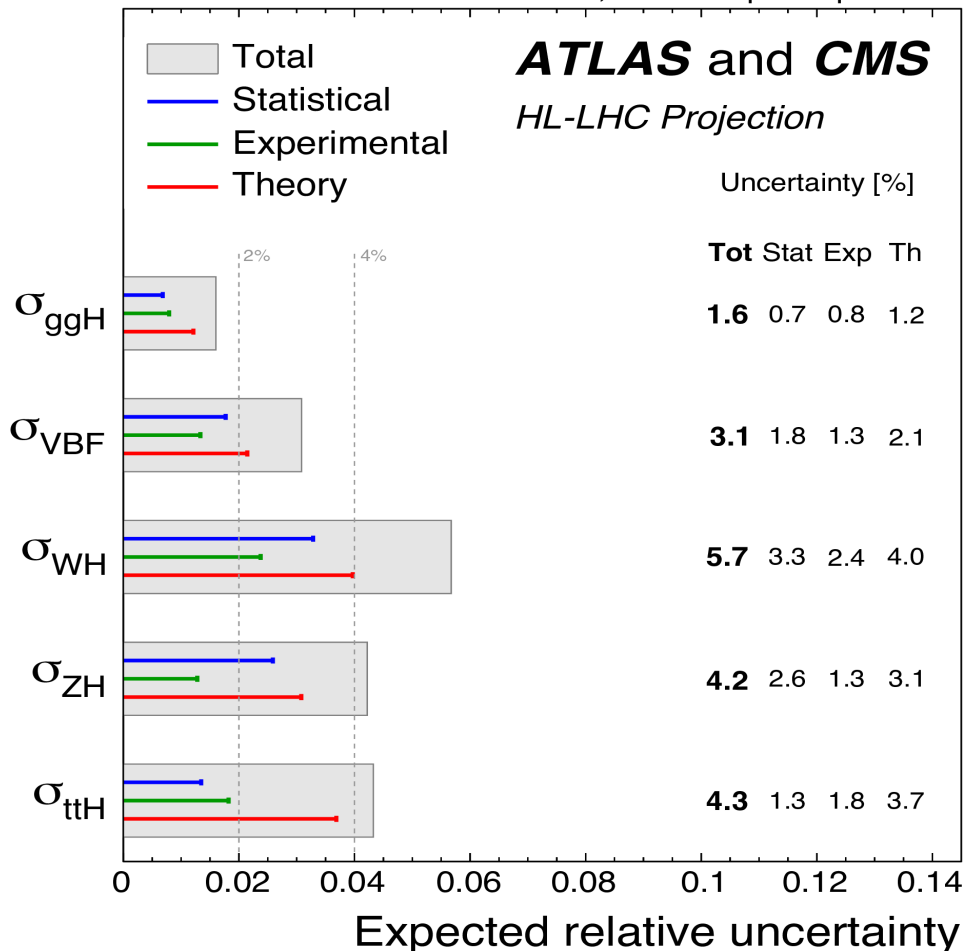


# Higgs boson measurements at HL-LHC

# Cross sections and Couplings

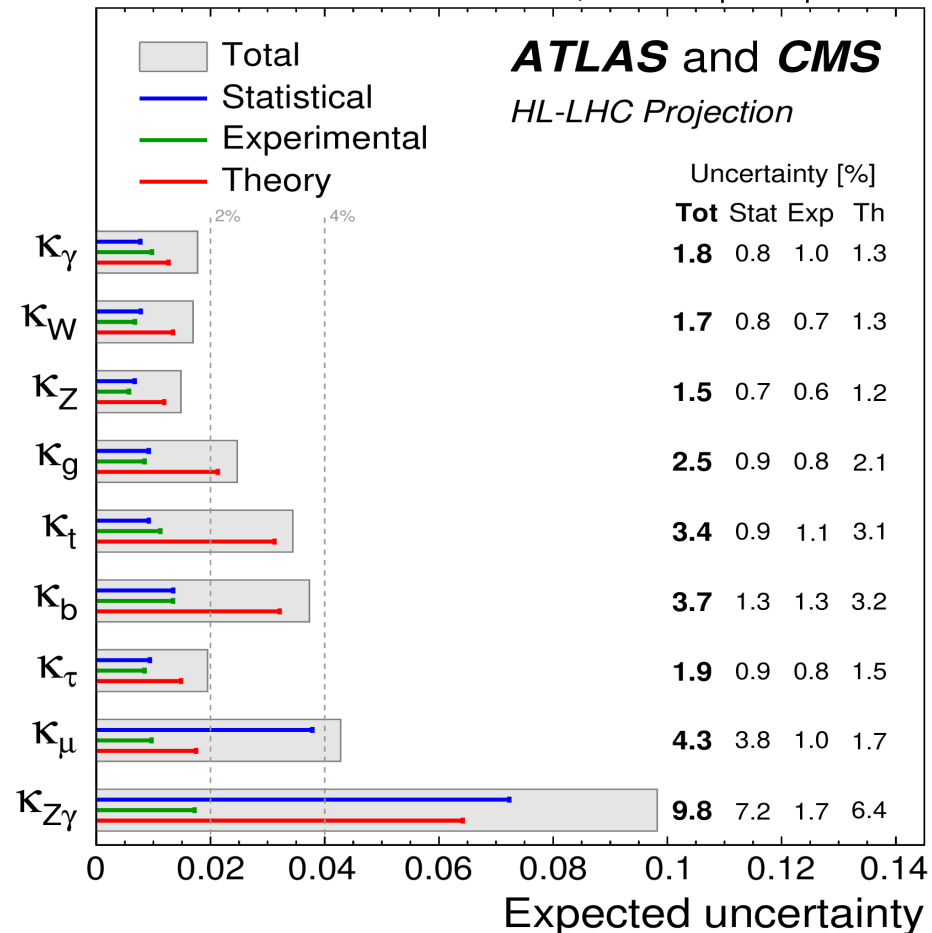
## Production cross sections

$\sqrt{s} = 14 \text{ TeV}$ ,  $3000 \text{ fb}^{-1}$  per experiment



## Couplings

$\sqrt{s} = 14 \text{ TeV}$ ,  $3000 \text{ fb}^{-1}$  per experiment

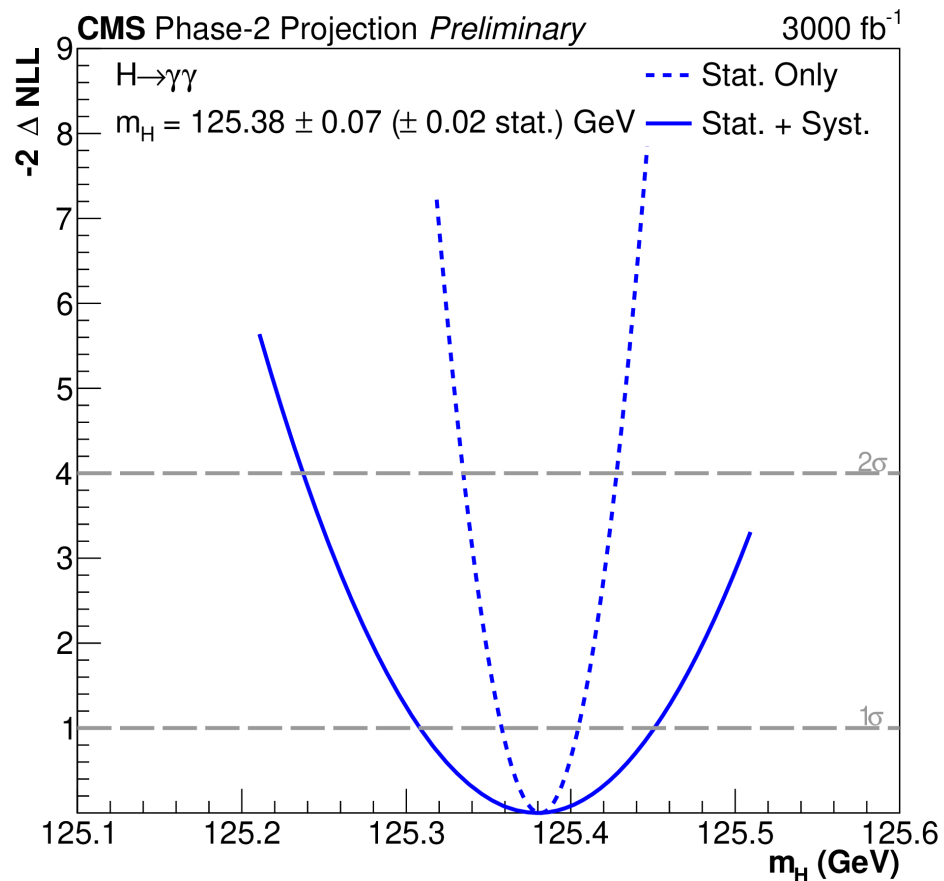


- Expected precision reaching 2 - 5% at the end of HL-LHC (CMS+ATLAS)
- Large impact of theory uncertainty in many cases (despite the /2)



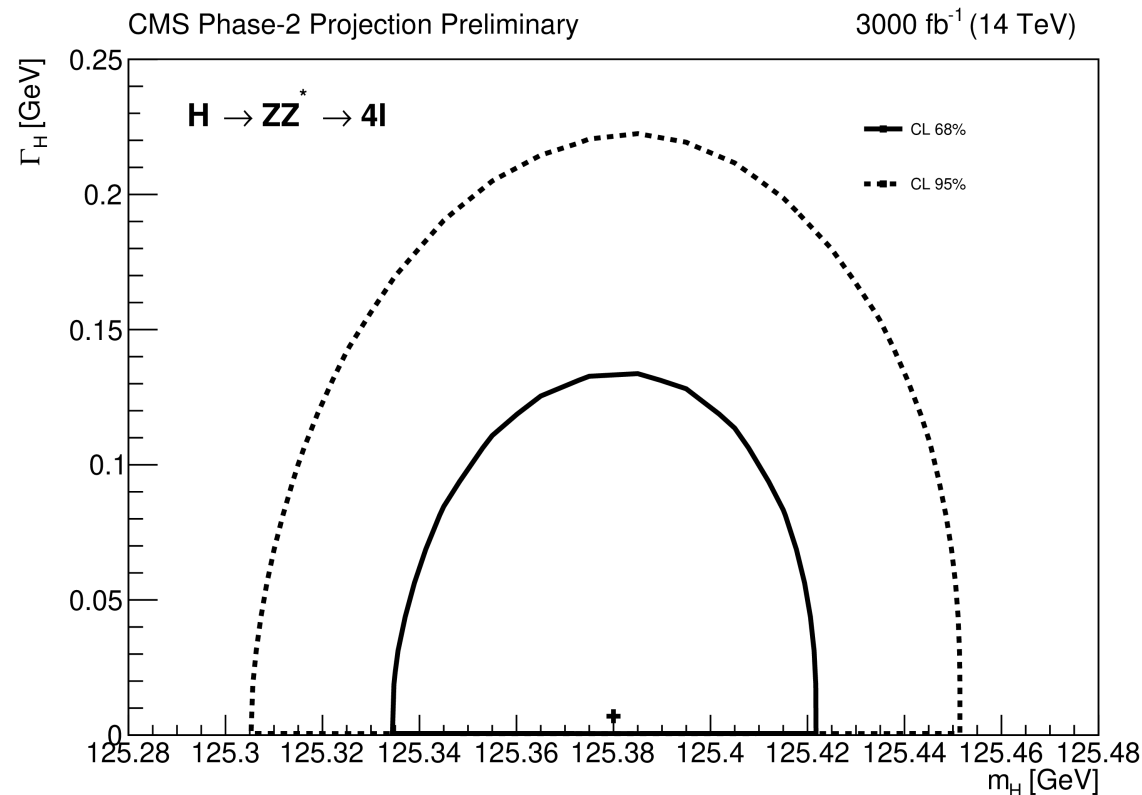
# Higgs Boson Mass and Width

## Mass in $H \rightarrow \gamma\gamma$



Total uncertainty on  $m_H$ : **70 MeV**  
Limited by photon energy scale ( $\sim 0.05\%$ )

## Mass vs width in $H \rightarrow ZZ \rightarrow 4\ell$



Total uncertainty on  $m_H$ : **25–30 MeV**  
comparable stat. and syst. unc.  
Direct constraint on width:  $\Gamma_H < \mathbf{177 \text{ MeV}}$

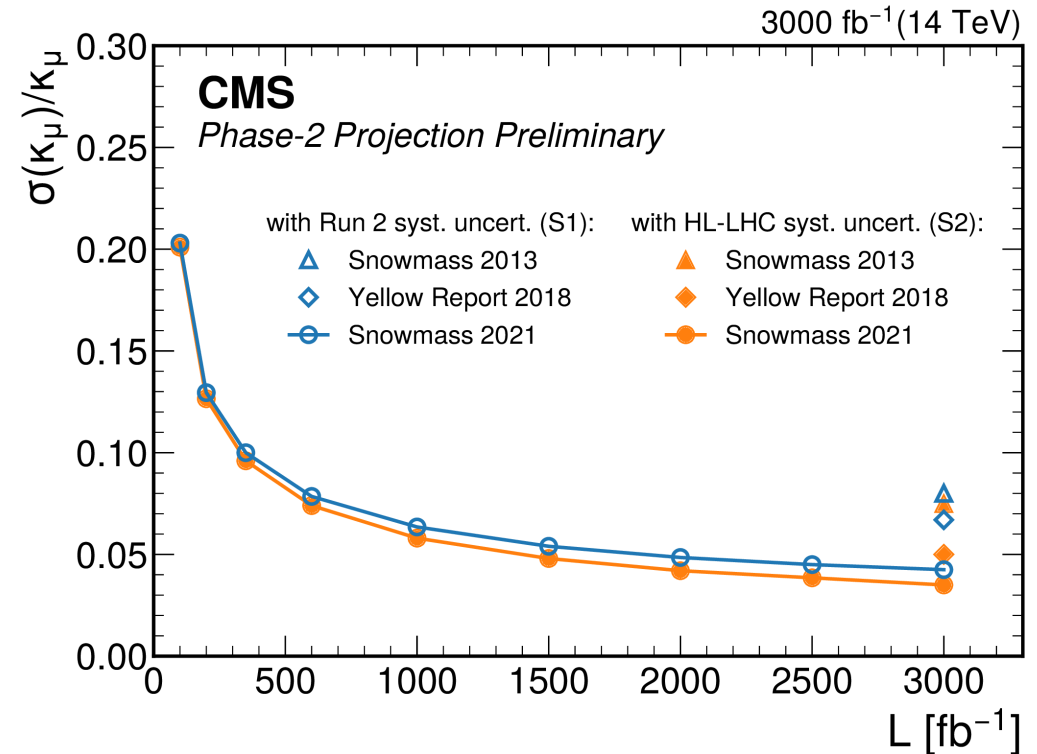
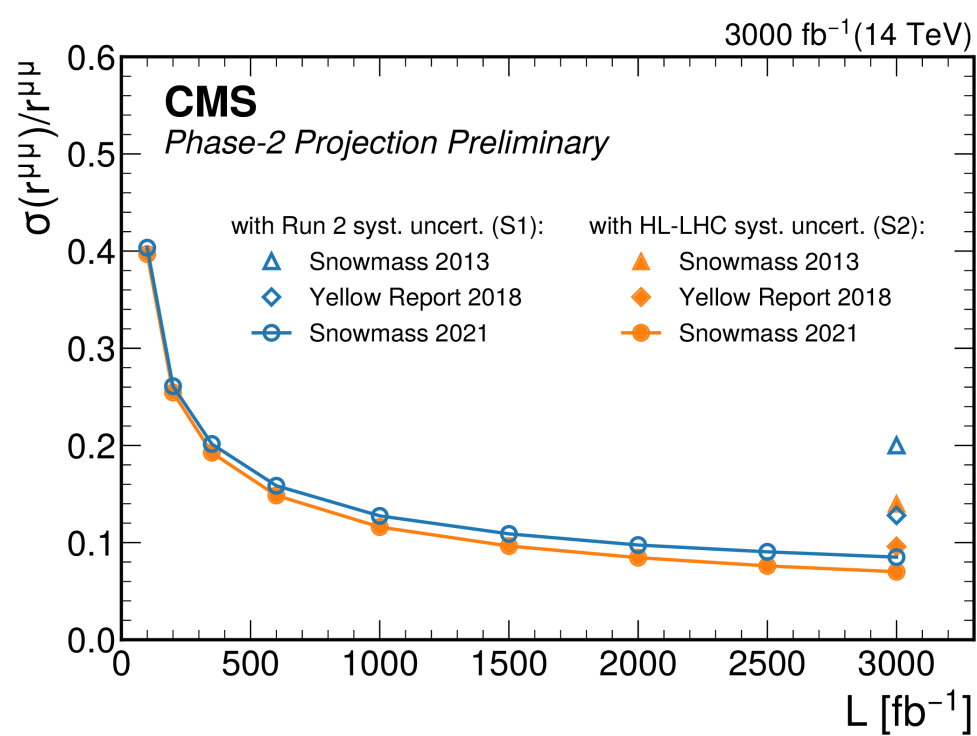
# Prospects for $H \rightarrow \mu\mu$

New projection based on the CMS full Run 2 analysis

**3–4% uncertainty on  $\kappa_\mu$  at HL-LHC**

~30% improvement compared to YR18

largely due to improved analysis strategy

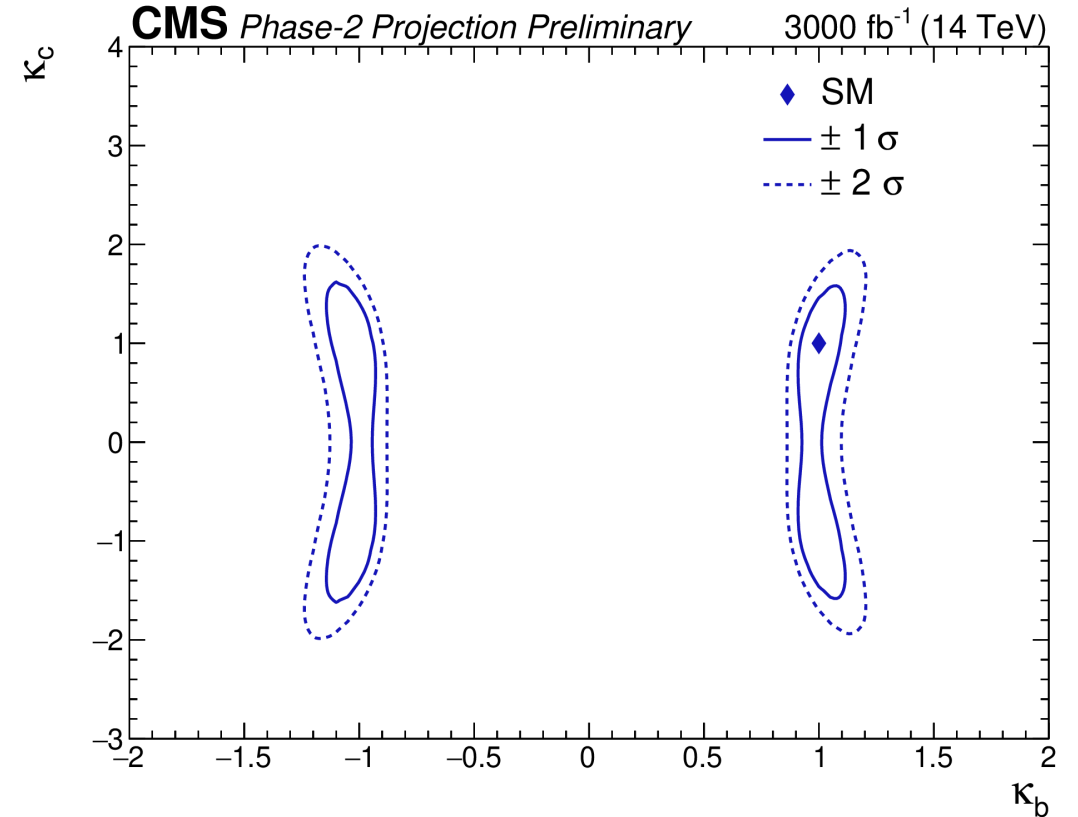
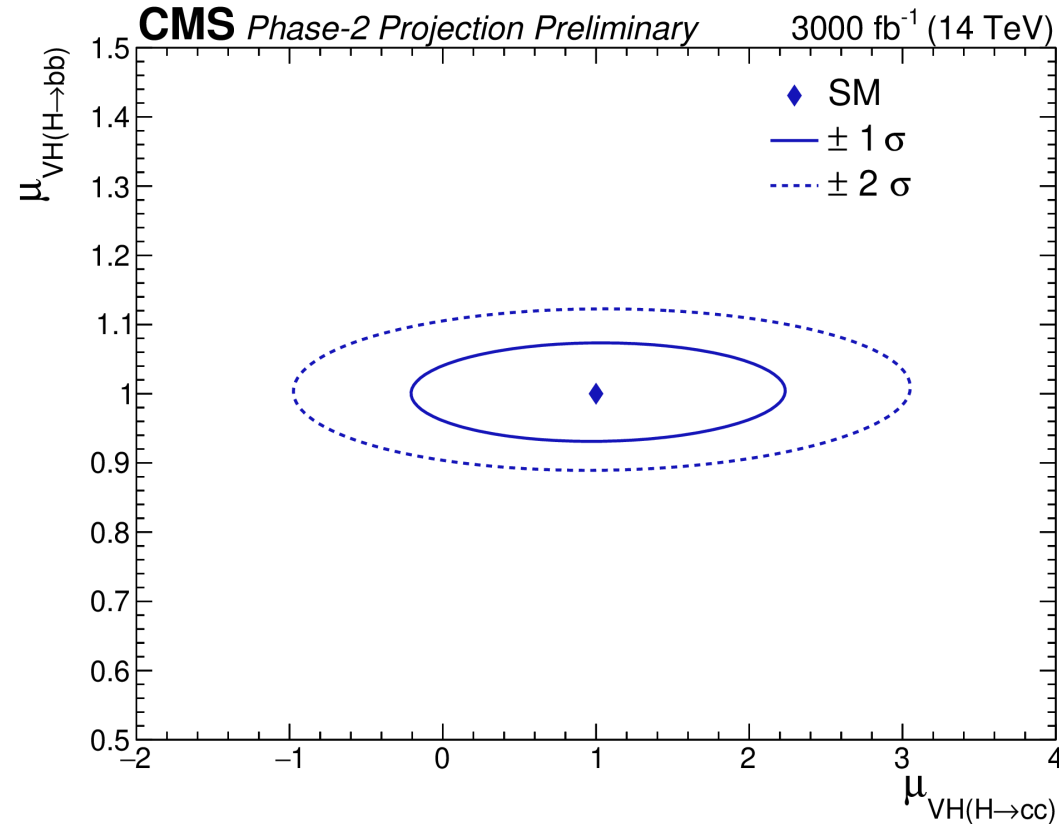


# Prospects of VH(H → cc) search

Projection of the Run 2 analysis to HL-LHC

Merged-jet topology with large-R jet  $p_T$

Simultaneous constraint of H → bb and H → cc



**Expected sensitivity approaches the SM value for the Higgs-charm coupling**

# ttH, H → bb with opposite-sign dileptons

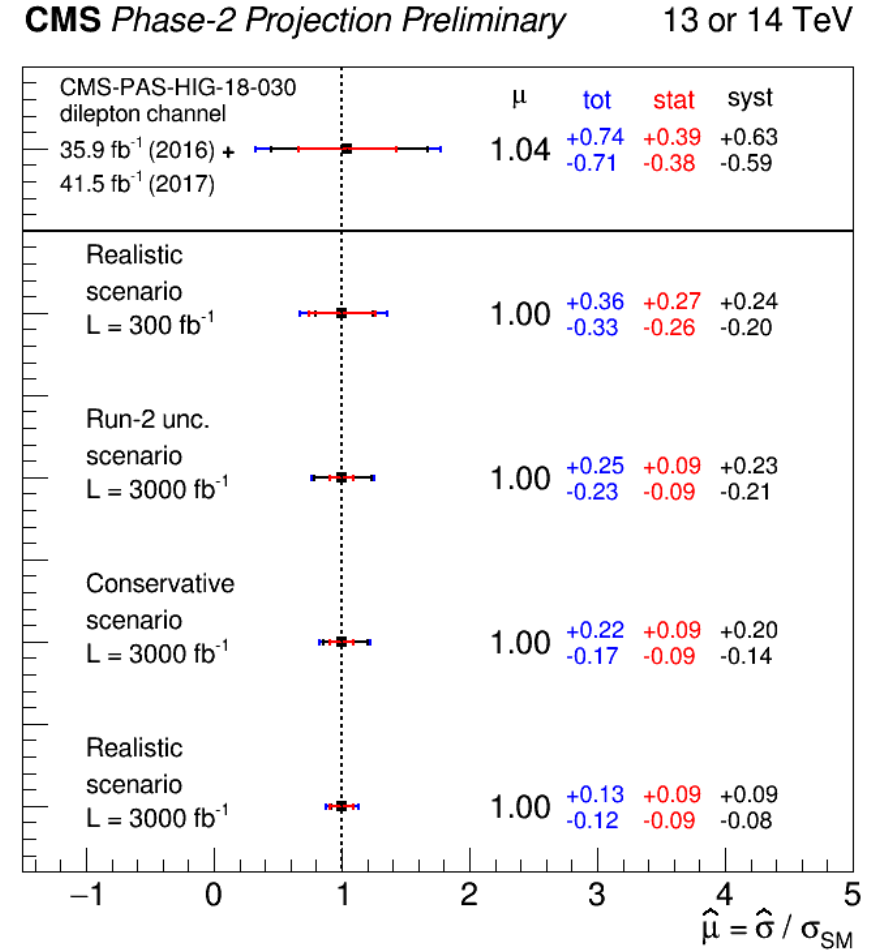
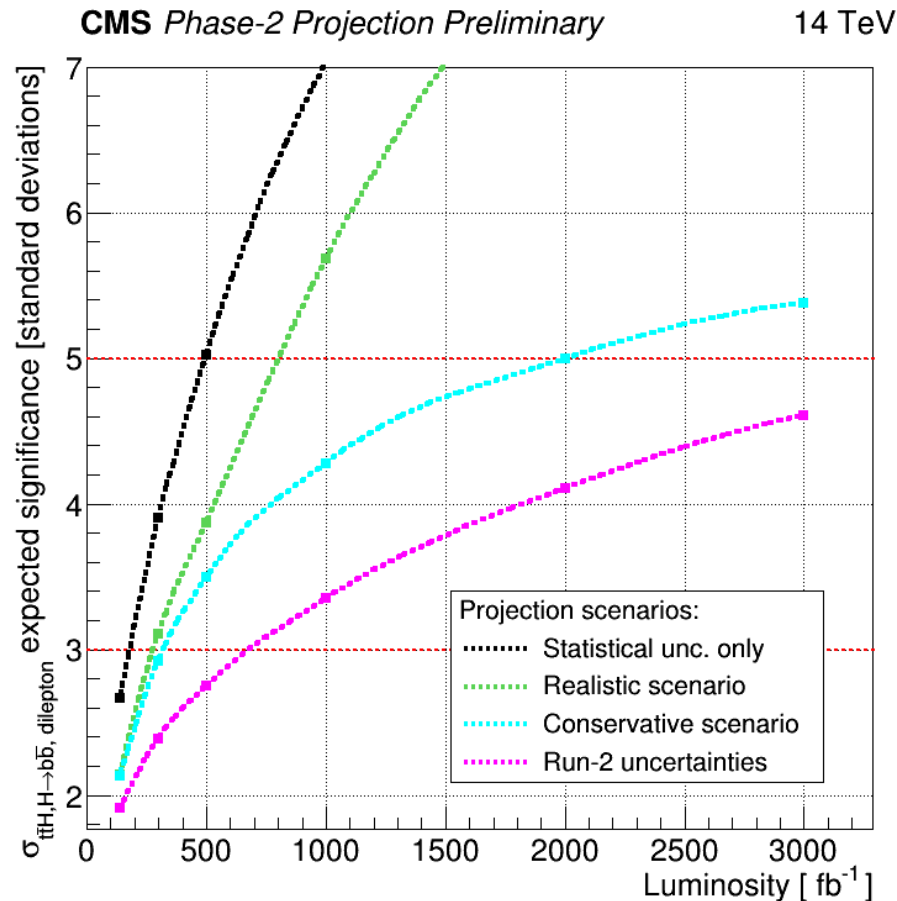
Projection of ttH, H → bb with new method based on CMS-PAS-HIG-18-030

Use a neural network to suppress tt+bb background

5σ discovery:  
possible with ~800 fb<sup>-1</sup>

Run 2 combined  
sensitivity:  
3.9 (3.5) σ obs (exp)

Expected significance vs.  
integrated luminosity;  
signal strength modifier  
for different systematics  
scenarios.

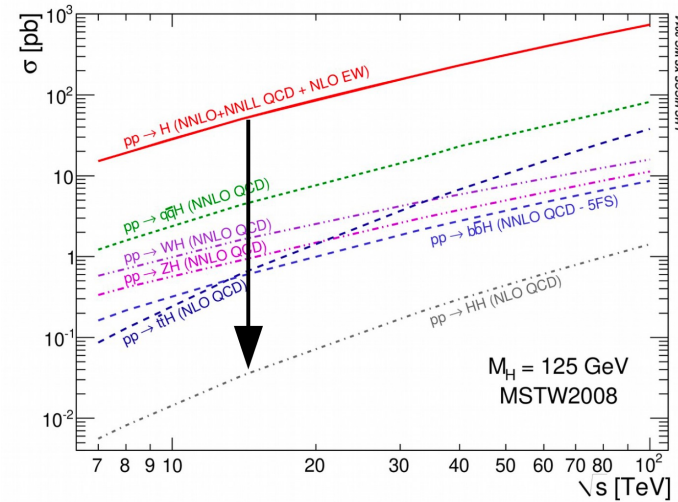
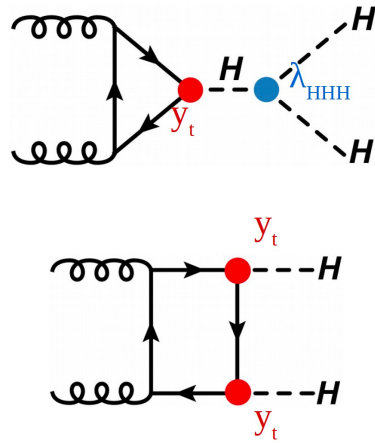




# Higgs boson pair (HH) prospects at HL-LHC

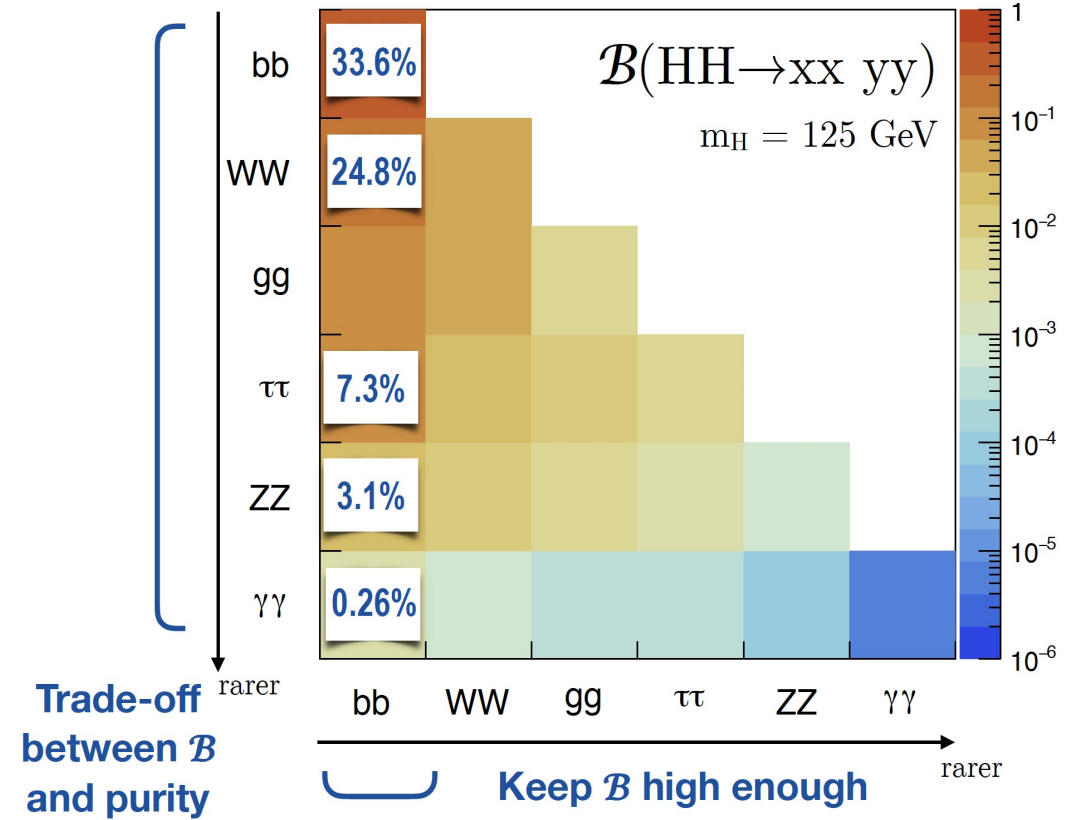
# Higgs boson pair production and decay

- **Non-resonant production:** rare process in the SM
  - Production is dominated by gluon fusion
    - Other rarer modes (ex: VBF HH production)
  - $\sigma(\text{gg} \rightarrow \text{HH}) \approx 0.1\% * \sigma(\text{gg} \rightarrow \text{H})$
  - Small  $\sigma_{\text{HH}} \Rightarrow$  need high luminosities
  - **Direct determination of  $\lambda$  from Higgs boson pair production**



- BSM contributions can modify the Higgs boson coupling parameters and modify the HH cross section:  
define  $\kappa_\lambda = c_{\text{hhh}} = \lambda_{\text{HHH}} / \lambda_{\text{HHH}}^{\text{SM}}$

## Decay



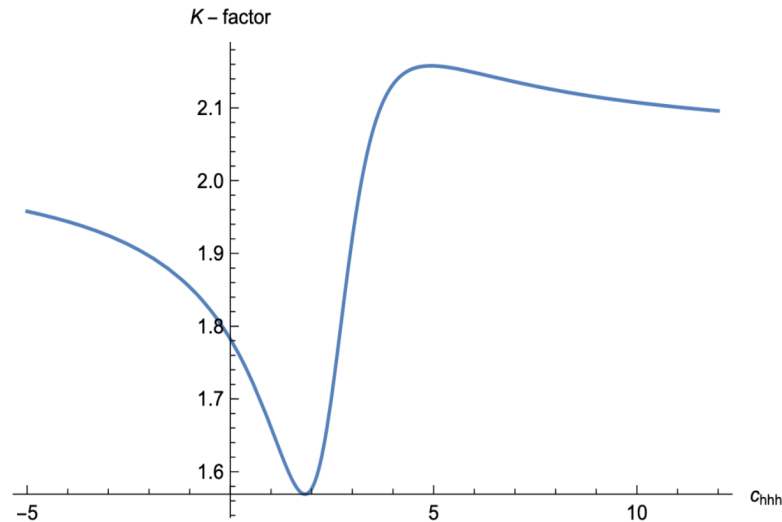
- Phenomenologically rich set of decay channels
  - Broad experimental coverage to increase sensitivity
- Many different signatures
  - All benefit from the upgraded CMS detector

# Higgs boson pair production cross section (1)

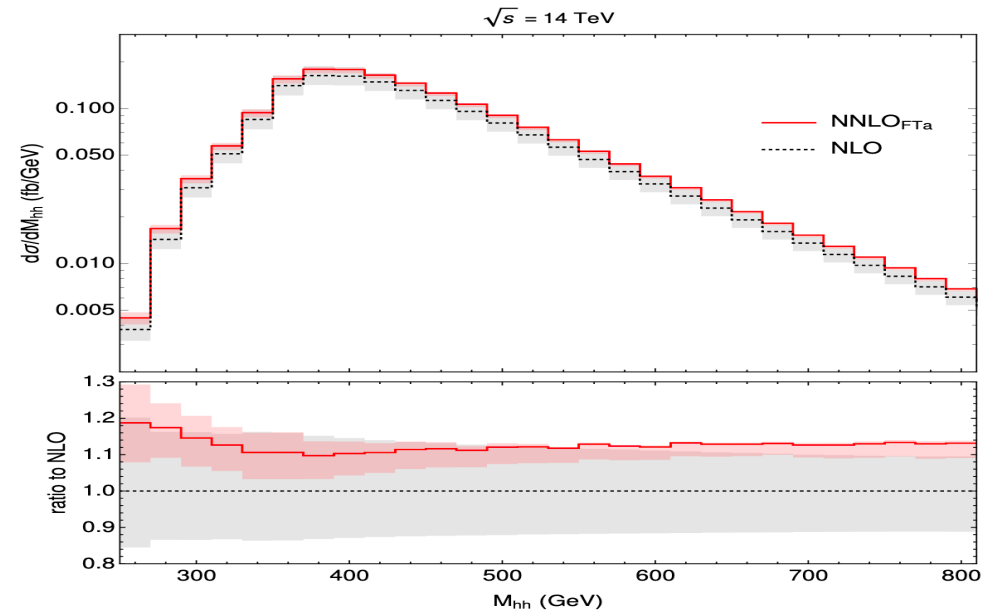
- SM calculation
  - **ggF**: State of the art NNLO with finite  $m_t$  effects
  - **Other production modes**: NLO with full  $m_t$  dependence
- Higgs **self-coupling variations** with full  $m_t$  dependence at NLO
  - LO to NLO K-factors vary from 1.57 to 2.16

$\sqrt{s}$ [TeV]	NNLO <sub>FTa</sub> [fb]	$m_t$ unc.	PDF unc.	$\alpha_S$ unc.	PDF+ $\alpha_S$ unc.
14	$36.69^{+2.1\%}_{-4.9\%}$	$\pm 2.7\%$	$\pm 2.1\%$	$\pm 2.1\%$	$\pm 3.0\%$
27	$139.9^{+1.3\%}_{-3.9\%}$	$\pm 3.4\%$	$\pm 1.7\%$	$\pm 1.8\%$	$\pm 2.5\%$

$\sqrt{s}$ (TeV)	ZHH	WHH	VBF HH	ttHH	tjHH
14	$0.359^{+1.9\%}_{-1.3\%} \pm 1.7\%$	$0.573^{+2.0\%}_{-1.4\%} \pm 1.9\%$	$1.95^{+1.1\%}_{-1.5\%} \pm 2.0\%$	$0.948^{+3.9\%}_{-13.5\%} \pm 3.2\%$	$0.0383^{+5.2\%}_{-3.3\%} \pm 4.7\%$
27	$0.963^{+2.1\%}_{-2.3\%} \pm 1.5\%$	$1.48^{+2.3\%}_{-2.5\%} \pm 1.7\%$	$8.21^{+1.1\%}_{-0.7\%} \pm 1.8\%$	$5.27^{+2.0\%}_{-3.7\%} \pm 2.5\%$	$0.254^{+3.8\%}_{-2.8\%} \pm 3.6\%$



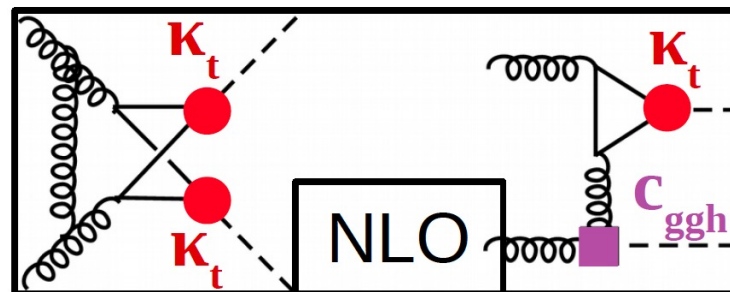
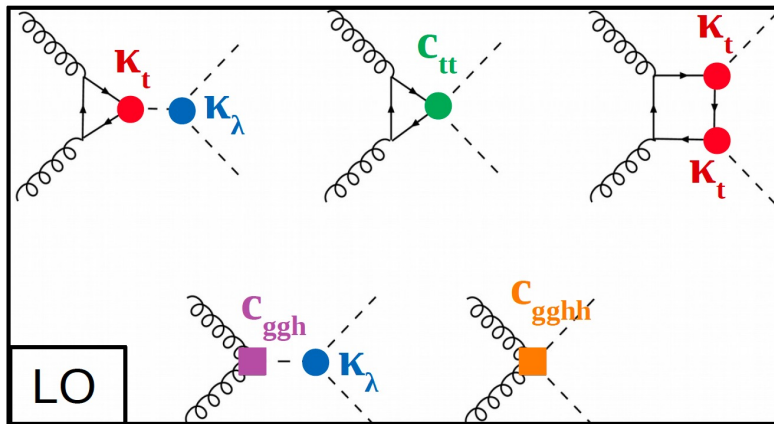
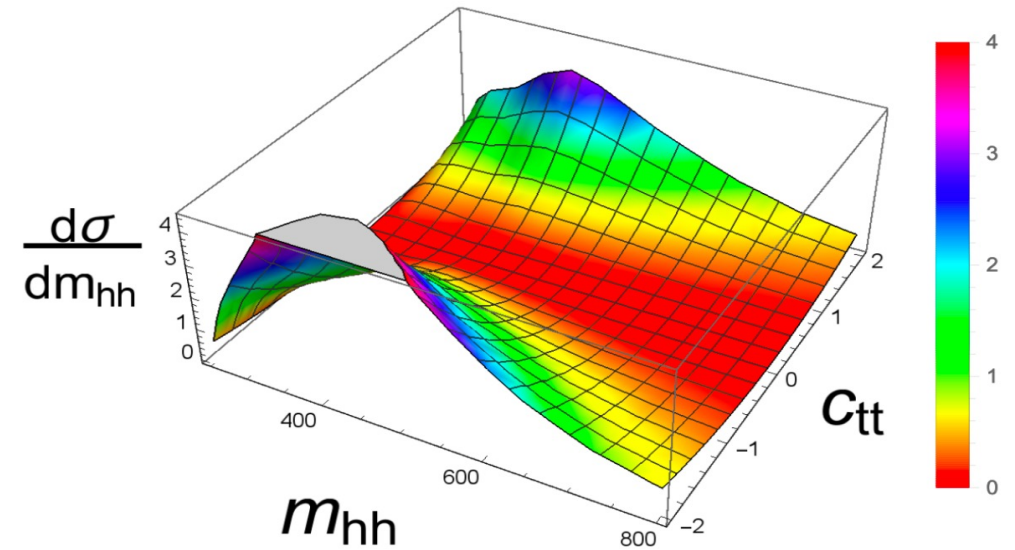
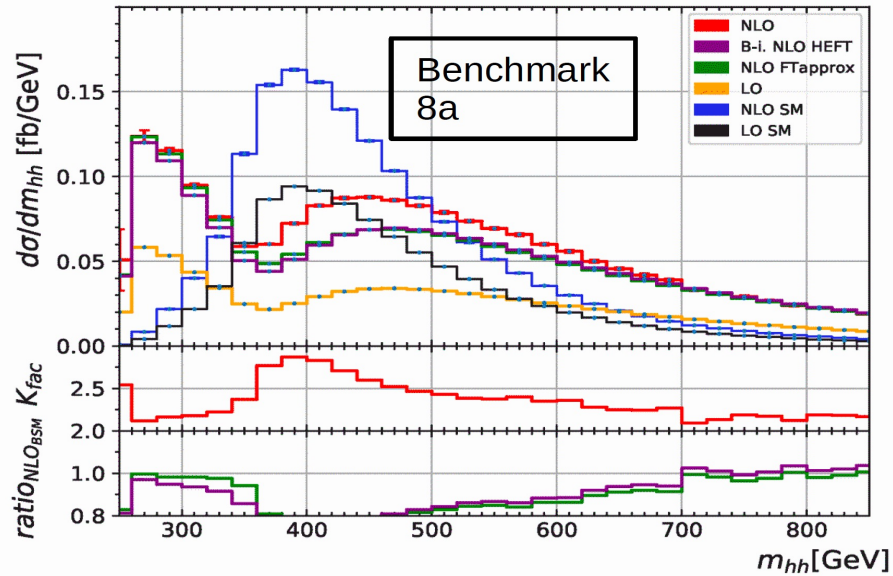
$m_{HH}$  differential cross sections



# Higgs boson pair production cross section (2)

- **BSM model:** Non-linear EFT
- Cross sections and  $m_{hh}$  at NLO QCD for some selected benchmark points

- Full NLO results are obtained for any values of the 5 modifying parameters



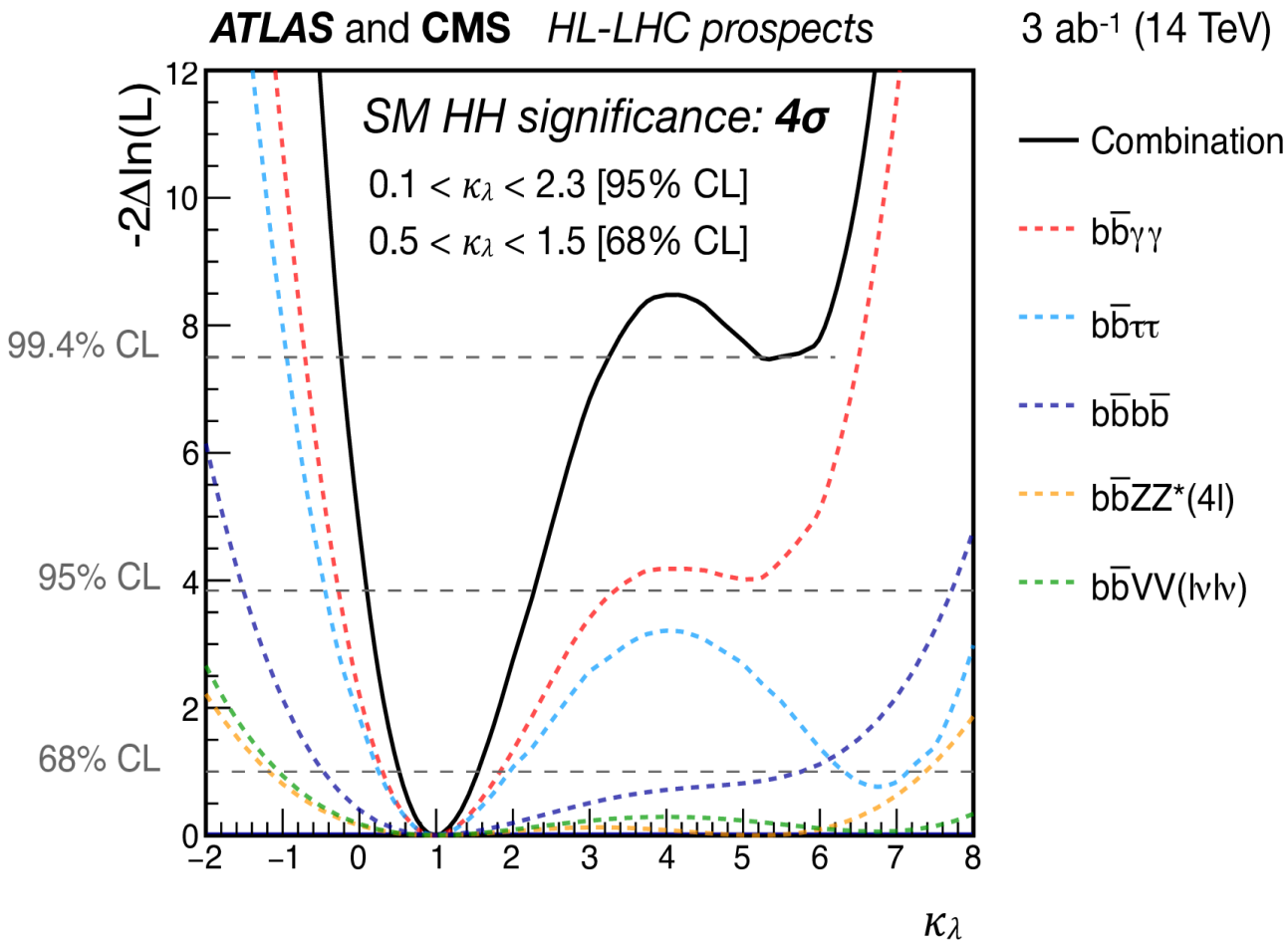
Benchmark	$C_{hhh}$	$C_t$	$C_{tt}$	$C_{ggh}$	$C_{gghh}$
5a	1	1	0	2/15	4/15
6	2.4	1	0	2/15	1/15
7	5	1	0	2/15	1/15
8a	1	1	1/2	4/15	0
SM	1	1	0	0	0



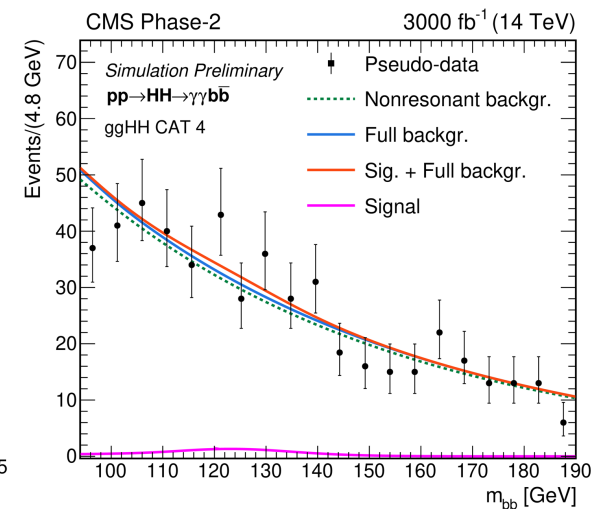
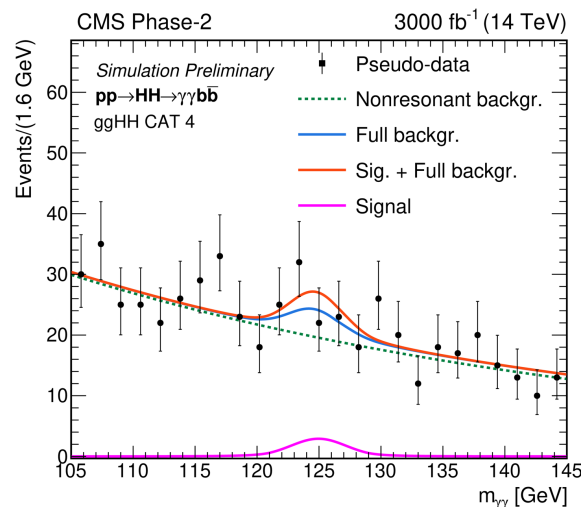
# HH Experimental prospects

- Expected **significance** with and without systematics at HL-LHC
  - 4 $\sigma$  expected with ATLAS+CMS!**

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \rightarrow b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \rightarrow b\bar{b}VV(l\nu\nu)$	-	0.59	-	0.56
$HH \rightarrow b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	



DNNs for signal/background discrimination in event selection.  
**HH  $\rightarrow$  bbyy : 2.16  $\sigma$  (for ggHH+VBFHH)**

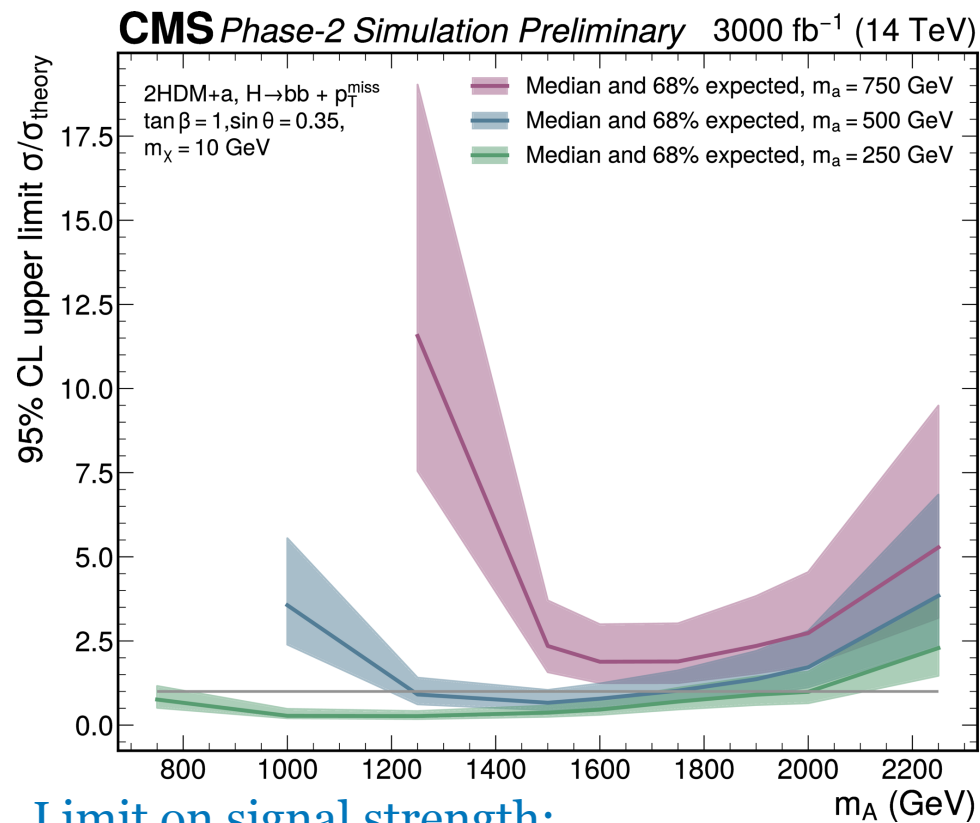
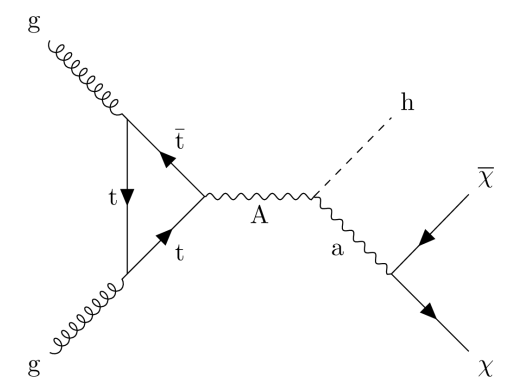


# Dark Matter

# H → bb + MET

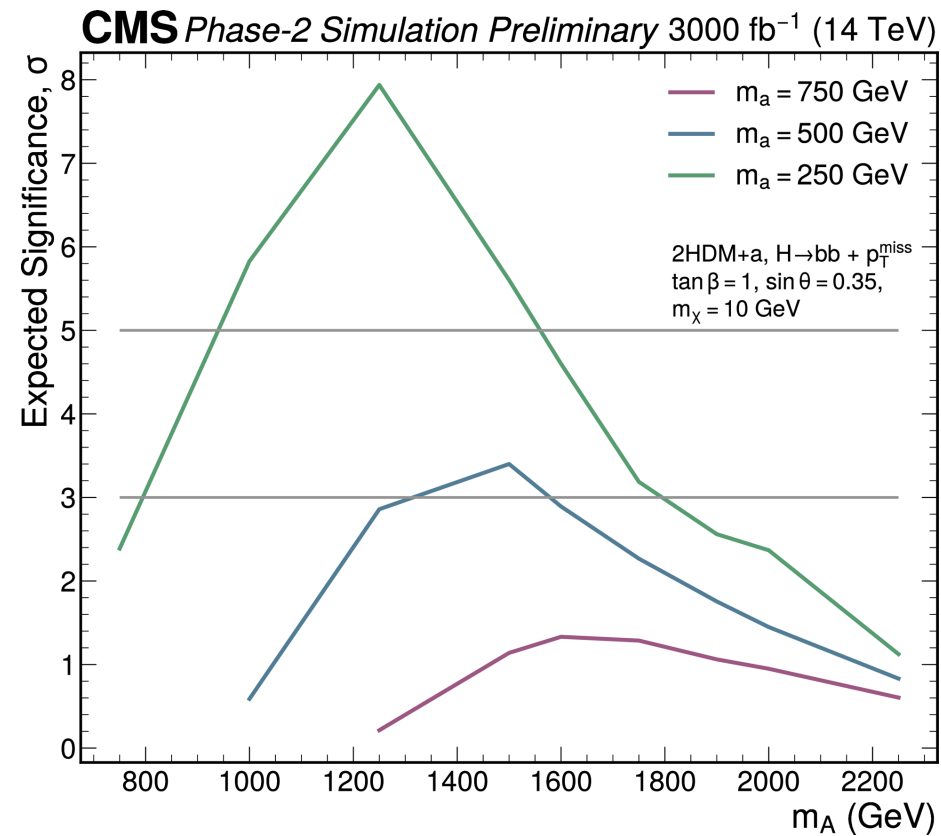
Search for boosted mono Higgs, with  $h \rightarrow bb + \text{dark matter}$  using Delphes:

- ML-based boosted Higgs tagging on AK8 jets;  $ET_{\text{miss}} > 200 \text{ GeV}$ .
- Interpretation in terms of a Type-II 2HDM+a model:  
 $\tan\beta = 1$ ,  $\sin\theta = 0.35$ ,  $m_\chi = 10 \text{ GeV}$



Limit on signal strength:

Exclude masses  $1 < m_A < 2 \text{ TeV}$  for  $m_a < 500 \text{ GeV}$



Significance:  $5\sigma$  discovery for  
 $m_A \sim 1\text{-}1.6 \text{ TeV}$ ,  $m_a = 250 \text{ GeV}$

# Summary

- Studies for the Yellow Report and White Paper covered a substantial part of the HL-LHC physics phase space.
- Exploring new ideas are encouraged, in particular final states only accessible at HL-LHC and studies exploiting Phase-2 detector features.
  - di-Higgs and long-lived particles are obvious examples.



*Thanks*